All-sky incoherent search for periodic signals with Explorer 2005 data

P Astone[1], D Babusci[3], M Bassan[4,5], P Carelli[6,5], G Cavallari[8], A Chincarini[2], E Coccia[4,5], S D'Antonio[5], M. Di Paolo Emilio [6,7], V Fafone[4,5], S Foffa[10], G Gemme[2], G Giordano[3], M Maggiore[10], A Marini[3], Y Minenkov[7], I Modena[4,5], G Modestino[3], A Moleti[4,5], G P Murtas[3], G V Pallottino[9,1], R Parodi[2], G Piano Mortari[6,7], G Pizzella[4,3], L Quintieri[3], A Rocchi[4,5], F Ronga[3], F. Saint Just [9,1], R Sturani[10], R Terenzi[11,4], G Torrioli[12,1], R Vaccarone[2], G Vandoni[8] and M Visco[11,5]

[1] *INFN, Sezione di Roma, Roma, Italy*

[2] *INFN, Sezione di Genova, Genova, Italy*

[3] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*

[4] *Dip. Fisica,* Università *di Roma "Tor Vergata", Roma, Italy*

[5] *INFN, Sezione di Roma Tor Vergata, Roma, Italy*

[6] Università *dell'Aquila, Italy*

[7] *INFN, Laboratori Nazionali del Gran Sasso, Assergi, L'Aquila, Italy*

[8] *CERN, Geneva , Switzerland*

[9] *Dip. Fisica,* Università *di Roma "La Sapienza", Roma, Italy*

[10] *Dep. de Phys.* Théorique, Université de Genève, Genève, Switzerland

[11] *INAF, Istituto Fisica Spazio Interplanetario, Roma, Italy and*

[12] *CNR, Istituto di Fotonica e Nanotecnologie, Roma, Italy*

The data collected during 2005 by the resonant bar Explorer are divided into segments and incoherently summed in order to perform an all-sky search for periodic gravitational wave signals.

The parameter space of the search spanned about 40Hz in frequency, over 23927 positions in the sky. Neither source orbital corrections nor spindown parameters have been included, with the result that the search was sensible to isolated neutron stars with a frequency drift less than $6 \cdot 10^{-11}$Hz/s.

No gravitational wave candidates have been found by means of the present analysis, which led to a best upper limit of $3.1 \cdot 10^{-23}$ for the dimensionless strain amplitude.

A.   Introduction

The search for periodic gravitational wave signals is a stimulating challenge for data analists because of the considerable amount of computing time required.

For blind searches, i.e. without any *a priori* knowledge about the source, a fully coherent analysis can not handle more than a few days of data because of the steep dependence of the size of the parameter space on the frequency resolution.

In [1] three data sets, each two days long, from the Explorer 1991 run have been coherently studied by means of the F statistics method [2] which led to and an upper limit of $1 \cdot 10^{-22}$ on h in the narrow band 921.00-921.76Hz.

A similar technique, applied in [3] to the most sensitive 10 hours of the the LIGO S2 run, led to an upper limit of $6.6 \cdot 10^{-23}$ for isolated neutron stars in the band between 160 and 728.8Hz.

With the widening of the frequency band, due to the advent of interferometers as well as to improvements in the readout of resonant detectors, several incoherent and semi-coherent methods have been conceived and employed.

In [4] the Hough transform technique has been applied to the LIGO S2 data to perform a blind search for isolated neutron stars on a set of narrow frequency bands in the range 200-400Hz, and a best upper limit of $4.43 \cdot 10^{-23}$ has been set.

In the present work, the simple technique of adding power spectra has been applied to the most sensitive 40Hz band of the 2005 run of the Explorer bar [5], resulting in a further improvement on the best upper limit on h, which is set to $3.1 \cdot 10^{-23}$ at 920.14Hz.

According to the results reported at the recent Amaldi7 conference, the analysis of the LIGO S4 run [6] is leading to a sensible improvement in this direction (about an order of magnitude); remarkably, the limit set in the present work is still competitive with the one coming from the S4 data in the same frequency band.
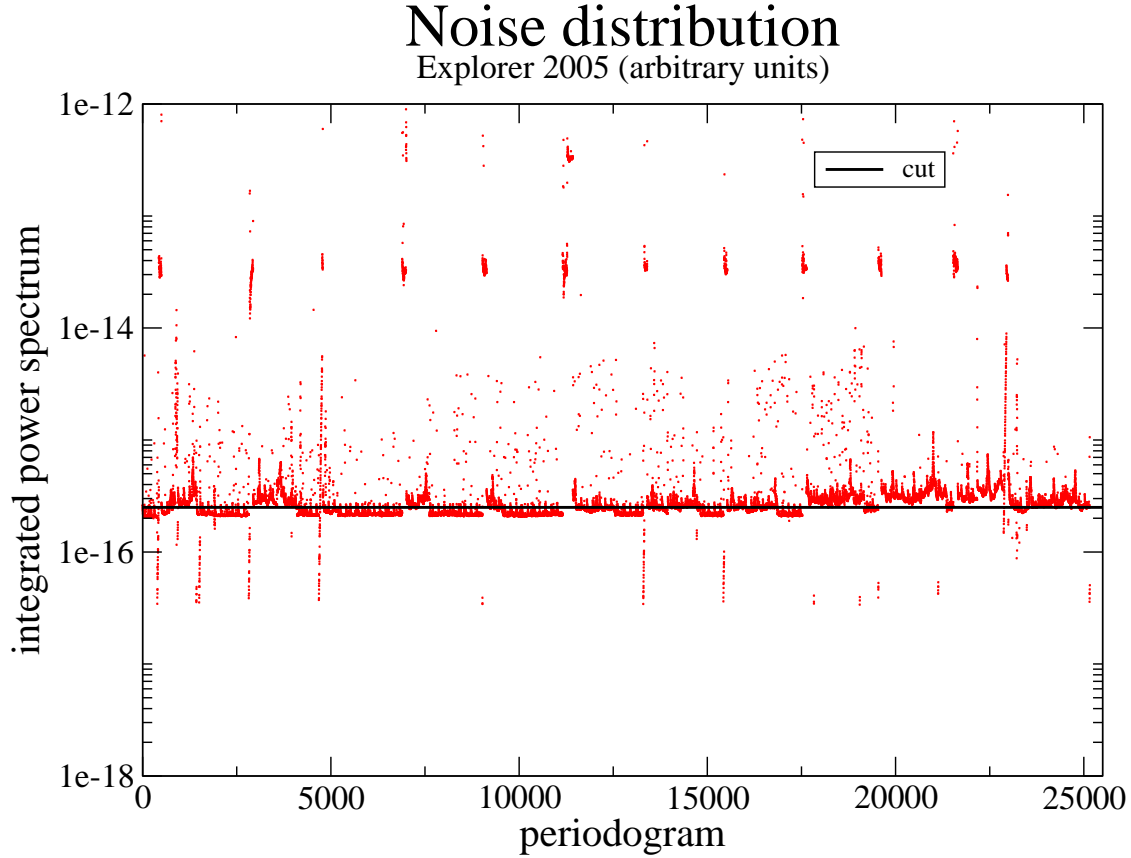
Figure 1: The noise level of Explorer during the 2005 run. The solid horizontal line is the cut applied to select the best spectra.

B. The data set

At the end of April 2005, after a short commissioning break, the resonant antenna Explorer was again *on air* and operated with the usual, remarkable duty cycle (86% from April to December 2005) and a good stability.

The data stream taken by the bar until the end of 2005 (after which the sensitivity curve has been modified) has been divided into 25161 segments, each about 14 minutes long. The most sensitive band of the Fourier transform of these segments, namely $N_f = 32178$ frequency bins in the range 885-925Hz, has been selected for the analysis.

A noise cut has been applied to the total power contained in each spectrum, with the purpose of discarding the noisy ones thus creating an homogeneous set of spectra. This allowed us to apply for the subsequent analysis the simple power addition method, without
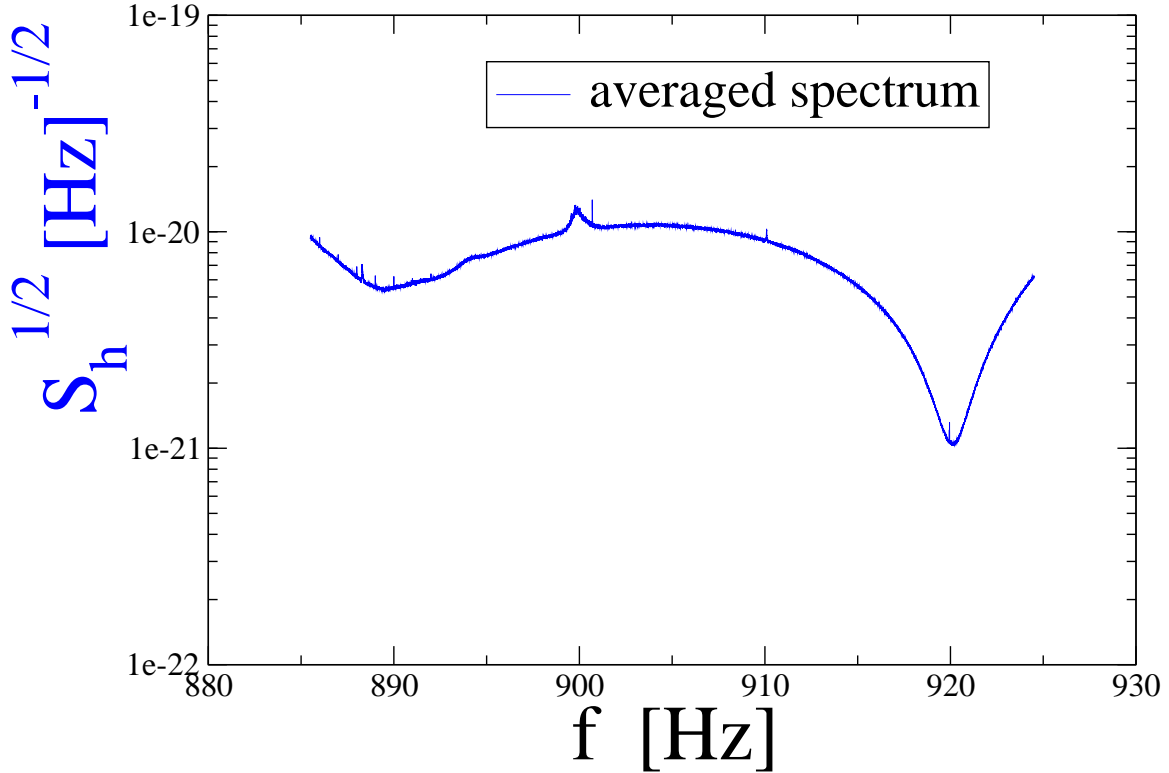
Figure 2: The square root of the average spectrum represents the typical Explorer sensitivity curve during the 2005 run.

weighting each spectrum with the corresponding noise level.

This selection led to the creation of a data set $\{S_i\}$ made of the $N_1 = 11749$ cleanest spectra (corresponding to an effective data time of 114 days), and of a second set containing just the best $N_2 = 3875$ (used to deal with the critical zones of the spectrum, corresponding to the resonant modes of the bar, around 888Hz and 920Hz).

The average sensitivity of the second data set is shown in Fig. 2 (the first set is similar except around the resonant modes); a few noisy lines may be noted, including small 1Hz harmonics on the left part.

C.   The analysis method

For a given direction $\hat{r}_j$ in the sky, the selected spectra have been deformed according to the Doppler shift formula

$$f_j^{\text{true}} \simeq f_{\exp}\left(1 - \frac{\vec{v}_{rel} \cdot \hat{r}_j}{c}\right)$$

and then summed and renormalized dividing by N_1 or by N_2:

$$\mathcal{S}_j(f_j^{\text{true}}) = \frac{1}{N_{1,2}} \sum_{i=1}^{N_{1,2}} S_i(f_j^{\text{true}}) \, .$$

The speed of the detector relative to the Solar System Baricenter has been computed thanks to the JPL ephemerides [7]. As the speed of the source have not been taken into account, the search is sensitive to isolated neutron stars, and not to those which are part of binary systems.

Spindown has also been neglected: given the frequency resolution of $1.2 \cdot 10^{-3}$Hz, this means being sensitive to an average frequency drift up to $6 \cdot 10^{-11}$Hz/s during the observation period.

The procedure has been repeated for any point of an optimized sky grid made of $N_{\text{sky}} = 23927$ possible directions, thus leading to the creation of a set $\{\mathcal{S}_j\}$ containing N_{sky} "deformed and summed" spectra.

The variance of the noise is obtained calculating, for each value of the frequency, the variance of the distribution of the N_{sky} deformed spectra. The result, whose square root is shown in Fig. 3, agrees with the general expectation, based on the central limit theorem, that

$$\sigma \simeq \frac{S_h}{\sqrt{N_{1,2}}} \, . \tag{1}$$

As expected, the plot shows an anomalous behavior of the noise variance in correspondence of the disturbances of the initial data set. These anomalous zones have not been taken into account for the candidate search, but have been included in the upper limit determination.

The detection threshold is fixed by the requirement that the false alarm rate should be less than 1%. According to Poisson statistics one has to impose

$$P(0, \lambda) = e^{-\lambda} > .99 \, ,$$

where the expected number of threshold crossings in absence of signal is
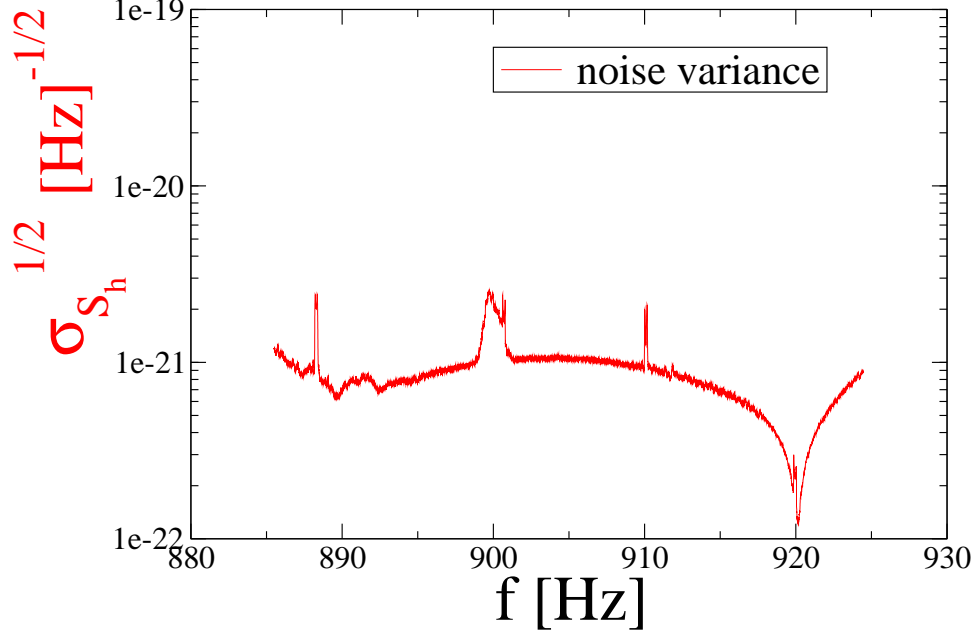
$$\lambda = p \cdot N_f \cdot N_{\text{sky}} \, ,$$

Figure 3: Noise variance of the set of deformed and summed spectra. To help comparison with Fig. 2, the square root of σ is actually shown.

being p the probability of false detection in a single frequency bin and for a single direction in the sky, and $N_f \cdot N_{\mathrm{sky}}$ the trial factor.

One thus finds the condition $p < 1.3 \cdot 10^{-11}$ which, assuming that the N_{sky} values of the shifted spectra at a given frequency bin are gaussian distributed, translates to a 7σ threshold.

In other words, a detection is claimed if, for some value of the frequency f, a given deformed spectrum $\mathcal{S}_j$ satisfies the condition

$$\mathcal{S}_j(f) - \bar{\mathcal{S}}(f) > 7\sigma(f), \tag{2}$$

being $\bar{\mathcal{S}}$ the average of the deformed spectra $\{\mathcal{S}_j\}$ as j spans over the N_{sky} sky grid points.

Since $h \propto \sqrt{S}$, to translate the detection threshold in h units one has to multiply the values shown in Fig. 3 by the factor

$$\sqrt{\frac{7}{T}} \cdot \sqrt{\frac{15}{4}},$$

where T is the length of each data segment and the factor $4/15$ (the average angular sensitivity of the bar over the solid angle) is introduced to compensate the fact that amplitude modulation has not been taken into account when summing the deformed spectra.
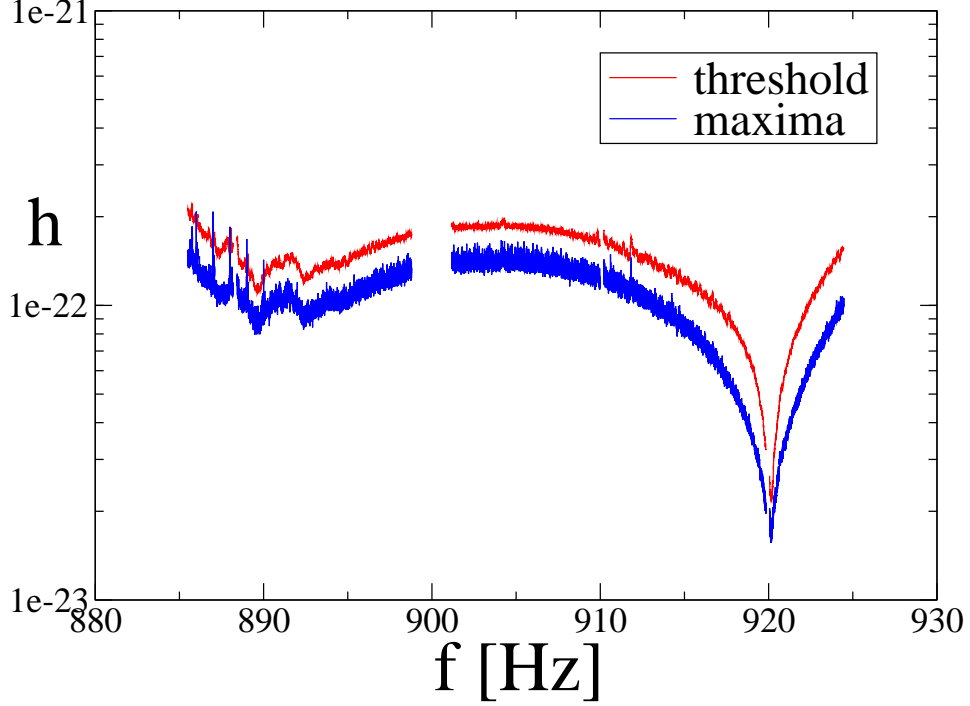
Figure 4: Detection threshold (red, upper curve) and maximal triggers (blue, lower). The 1Hz disturbances on the left have been left only for illustrative purpose and cannot be considered as genuine threshold crossings.

D. Results

1. Cadidate search

The threshold is shown in red in Figure 4, while the blue line is the maximum value of h found, at any given frequency bin, among the set of the N_{sky} spectra according to the following formula:

$$h_{\max}(f) = \max_j \left[\sqrt{ \frac{15}{4} \frac{\mathcal{S}_j(f) - \bar{\mathcal{S}}(f)}{T} } \right] .$$

The anomalous regions of the spectrum have been cut out, since it is not reasonable to assume that they follow a gaussian distribution. To illustrate the point, the 1Hz disturbances have been keft in Figure 4, to show that they would have produced fake candidates, if they had been included in the analysis.

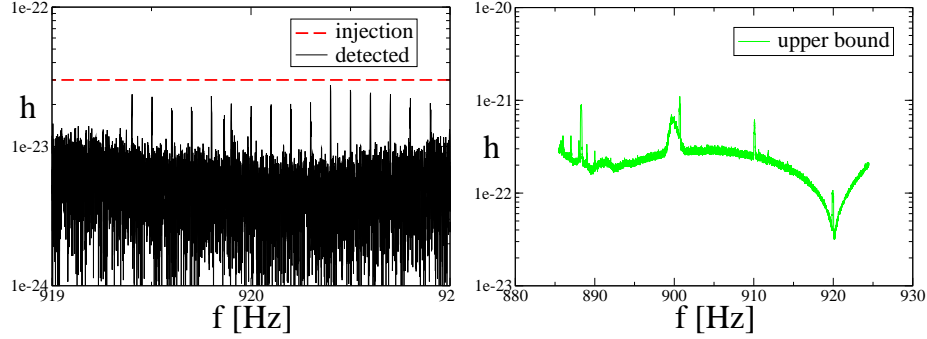With these specifications, the maxima are never above the threshold, and thus no candi-

Figure 5: On the left, the outcome of the 16 injections, with initial amplitude given by the dashed red line. On the right, the upper limt curve.

dates have been found.

2. Software injections and upper limit

To find an upper limit on h, a variation of the loudest event method [8] has been applied. This method allows to determine an upper limit starting from the loudest event present in a data stream, irrespectively of the fact that such an event may be due to noise or to a real signal. The idea is basically that if a strong real signal would have been present during the data taking, it would have produced an event louder than the loudest event actually recorded. This idea can be made quantitative by studying the detection efficiency of the experiment, for example by performing software injections at various SNR's.

In our case, we have a loudest event for any frequency bin, and all these events form precisely the curve of maxima depicted in Figure 4. As a preliminary step, we had to determine our detection efficiency by injecting fake periodic signals in the Explorer data stream and finding out how hey did loook like after the analysis chain: the left plot of Figure 5 shows for instance the result of 16 injections of signals with $h = 3 \cdot 10^{-23}$, equally spaced in frequency by 0.1Hz starting from 919.4Hz, and coming from randomly chosen directions in the sky. Then, the upper limit at 95% c.l. at has been determined for each frequency bin as the lowest injected amplitude which had produced a signal larger than the actual maximum at least in 95% of the cases.

The right plot on Figure 5 shows the result, i.e. the curve of h upper limit at 95%

confidence level: the minimum is $3.1 \cdot 10^{-23}$ at 920.14 Hz.

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